

Neutral Pion Production in the Threshold Region

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Abstract

We give an overview of the physics motivation and evolution of the neutral pion photoproduction measurements in the threshold region conducted in the A2 collaboration at MAMI. The latest two experiments have been performed with the almost 4π Crystal Ball detector. The first was with a linearly polarized photon beam and unpolarized liquid-hydrogen target. The data analysis is now complete and the linearly polarized beam asymmetry along with differential cross sections provide the most stringent test to date of the predictions of Chiral Perturbation Theory and its energy region of convergence. More recently a measurement was performed using both circularly polarized photons and a transversely polarized butanol frozen-spin target, with the goal of extracting both the target and beam-target asymmetries. From these we intend to extract πN scattering sensitive information for the first time in photo-pion reactions. This will be used to test isospin conservation and further test dynamics of chiral symmetry breaking in QCD as calculated at low energies by Chiral Perturbation Theory.

1 Introduction

Low-energy pion-nucleon interactions and photo-pion production are of special interest because the pion, the lightest hadron, is a Nambu-Goldstone Boson which by its existence represents a clear signature of spontaneous chiral symmetry breaking in QCD [1, 2]. The dynamic consequences are that the production and scattering of low-energy pions are weak in the s-wave [3] and strong in the p-wave [2, 4, 5], as is seen clearly in the data for πN scattering and the $\gamma N \rightarrow \pi N$ reaction [6]. The physical manifestations include the strong tensor force in the long range (pion-exchange) part of the nucleon-nucleon potential [5]. The s-wave amplitudes are small in πN scattering and in the $\gamma^* N \rightarrow \pi^0 N$ reaction, where γ^* is a real or virtual photon. This is true since they vanish in the chiral limit ($m_u, m_d, m_\pi \rightarrow 0$) [4, 5]; their small, but non-vanishing values are measures of explicit chiral symmetry breaking. Moreover, they are isospin violating [7, 8] since $m_u \neq m_d$ [9, 10], in addition to electromagnetic effects.

The fact that the interactions and production amplitudes are weak at low energies due to the spontaneous breaking of chiral symmetry in QCD has led to an effective field theory called Chiral Perturbation Theory (ChPT) [11]. Despite its name ChPT is not perturbative in the sense that in QCD at high energies the coupling constant α_s becomes small and normal perturbation theory is accurate. At low energies, where we are working, α_s becomes large and leads to confinement of the quarks and gluons so that it is preferable for the effective theory to deal with the pions and nucleons (and not the quarks and gluons) as the degrees of freedom. The weak hadron-pion interaction at low energies is what leads to a perturbative approach (similar to a Taylor series) at low energies; this is characterized by the small parameters $q/\Lambda_\chi, m/\Lambda_\chi$ where q and m are the pion momentum and mass, and $\Lambda_\chi \simeq 1$ GeV is the chiral symmetry breaking scale. The lowest order ChPT calculations reproduced the pre-QCD low-energy theorems [12]. The higher order corrections are defined by a well defined set of counting rules which govern the forms of the interactions and Feynman diagrams that enter the calculations at any specified order [11]. Due to the underlying spontaneous chiral symmetry breaking, the higher order interactions all contain

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derivatives, which makes the p-wave interactions strong leading to the appearance of the low lying Δ resonance in the πN system. One recently noticed consequence of the weak s-wave and strong p-wave is the surprisingly early significance of the contribution of the d-waves in the $\gamma p \rightarrow \pi^0 p$ reaction [13]. Symmetry imposes a strict form for each term in the interaction but does not prescribe its magnitude [4, 11]. In practice these parameters (which are low-energy constants) have been obtained by fitting to data and approximately agree with model estimates. More recently the low-energy constants have been obtained with lattice calculations which have provided a striking confirmation of their values [14]. This has been obtained in the purely mesonic sector (e.g. $\pi - \pi$ scattering) for which exact agreement between experiment [15] and theory [16] has been obtained. This agreement required the introduction of a unitary cusp in $\pi - \pi$ scattering due to isospin breaking originating in the isospin breaking π^0, π^\pm mass difference [16] similar in origin to the unitary cusp in the $\gamma p \rightarrow \pi^0 p$ reaction in the vicinity of the $\gamma p \rightarrow \pi^+ n$ threshold [17]. For the pion-nucleon system, the introduction of the nucleon is an additional complication for the theory which makes the convergence more difficult and therefore the calculations are more involved and less accurate than in the purely mesonic sector. We are presently at the stage where a careful experimental comparison of theory and experiment as a function of energy is required to ascertain the accuracy and the region of validity for this theory for the $\gamma \pi N$ system. As has been stressed [18], any serious discrepancy between these calculations and experiment must be carefully examined as a potential violation of QCD; and understanding of QCD in the non-perturbative region has been considered one of the top ten challenges in all of physics.

Over an extended period of time the efforts of the A2 collaboration at Mainz have been focused on accurate measurements of low-energy γN Compton scattering and pion production reactions to perform tests of the ChPT predictions. Study of the $\gamma p \rightarrow \pi^0 p$ reaction started with the original MAMI accelerator and a small detector to observe the $\pi^0 \rightarrow \gamma\gamma$ decay [19]. This followed with increasingly more accurate experiments to obtain the relatively small cross section [20, 21]. A parallel effort was also carried out at Saskatoon [22] during this period. The Mainz work has been building up to the sensitive spin observables [21]. The present generation photo-pion production experiments that we are concentrating on include accurate measurements of the cross sections, polarized photon asymmetries, and polarized target and beam-target asymmetries T and F (defined below). These experiments have been carried out with circularly and linearly polarized, tagged photons and with the almost 4π Crystal Ball and TAPS detector system.

With the exception of pionic atoms, the study of low-energy πN scattering is limited by the fact that pion beams decay, so that experiments below a kinetic energy of $\simeq 20$ MeV are generally not feasible [23]. We are pioneering measurements of πN scattering at low energies as a final state interaction in pion photo-production [17, 24, 25] through the use of the transverse polarized target asymmetry (time reversal odd) observable [26]. Photo- and electro-production studies on proton targets involve the $\pi^0 p, \pi^+ n$ charge states while conventional pion-proton interactions are in the $\pi^\pm p, \pi^0 n$ states. This is an excellent opportunity for testing isospin symmetry which is predicted to be broken by both electromagnetic and strong interactions due to the mass difference of the up and down quarks [7, 8, 9, 10]. The program for these measurements has been laid out in a review article on threshold photo-pion physics [25]. These experiments will also provide very stringent tests of dynamical models [27] and predictions based on chiral symmetry breaking in QCD.

2 Photon Asymmetry

In December 2008 we performed an investigation of the $\vec{\gamma} p \rightarrow \pi^0 p$ reaction with a linear polarized photon beam and a liquid H_2 target using the Glasgow-Mainz photon tagger and the CB-TAPS detector system in the A2 hall at MAMI. The purpose was to perform the most accurate measurement to date of the differential cross section from threshold through the Δ region, and to greatly

improve our previous polarized photon asymmetry measurement [21]. The original experiment was conducted using the TAPS detector alone as shown in Figure 1. Note that this detector set-up

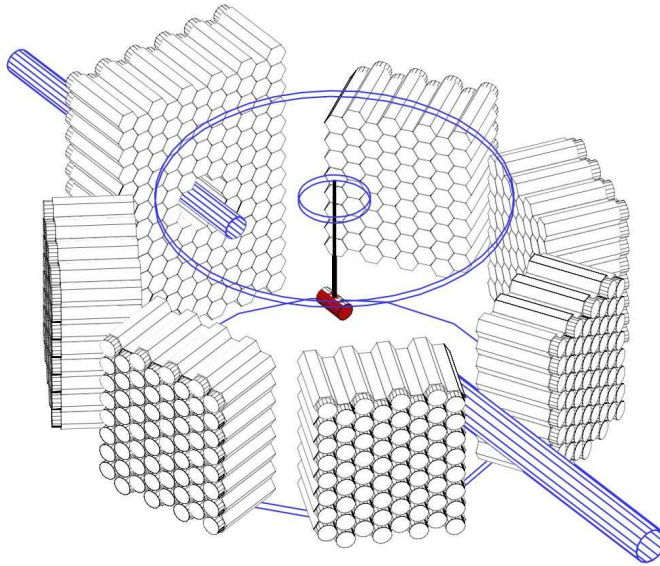


Figure 1: The TAPS detector in the π^0 -detection configuration. The solid-angle coverage is approximately 30% of 4π .

covered only about 30% of 4π , meaning that the detection efficiency for the two-photon channel of π^0 decay was on the order of 10%. The more recent experiment made use of the CB-TAPS set-up shown in Figure 2, which covers $\approx 96\%$ of 4π , resulting in a detection efficiency for the π^0 channel of roughly 90%. This fact alone made for a large improvement in the accuracy and counting rates for the new measurement. In addition, a higher electron beam energy was used which resulted in a significant increase in the degree of polarization for the incident photon beam. The other main difference between the TAPS and CB-TAPS measurements is that sufficient empty target data was taken for the latter, which turned out to be crucial due to the contribution to the asymmetry from the 0^+ nuclei in the kapton target windows. Due to poor statistics in the TAPS experiment, the polarized photon asymmetry, Σ , was integrated over the entire incident photon energy range, leading to data only at the cross section weighted energy average of 159.5 MeV.

The data analysis is close to finished and the results for the differential cross section and photon asymmetry are shown in Figure 3 at one photon energy (163.9 MeV) to give an idea of the accuracy. We have photon asymmetries from just above threshold in 2.4-MeV-wide bins, and differential cross sections from threshold into the Δ region. Fitting of the data has commenced for the low-energy constants in ChPT [28] in collaboration with C. Fernández Ramírez. The solid curves in Figure 3 are the ChPT calculations using s-, p-, and d-waves [13] with the low-energy parameters fit to the data. A comparison of the new CB-TAPS data with the original TAPS measurement is given in Figure 4 along with the ChPT calculations with updated low-energy parameters and the 2001 version of the DMT dynamical model [27].

With the use of a model-independent partial-wave analysis, one can extract various coefficients from the differential cross sections and photon beam asymmetry, and then comparison can be made between the extracted coefficients and the theory predictions. The s-, p-, and d-wave multipoles then appear only in the coefficients which allows for a very direct comparison of theory and experiment. In particular, the differential cross section can be expanded in terms of the pion CM angle, θ , in

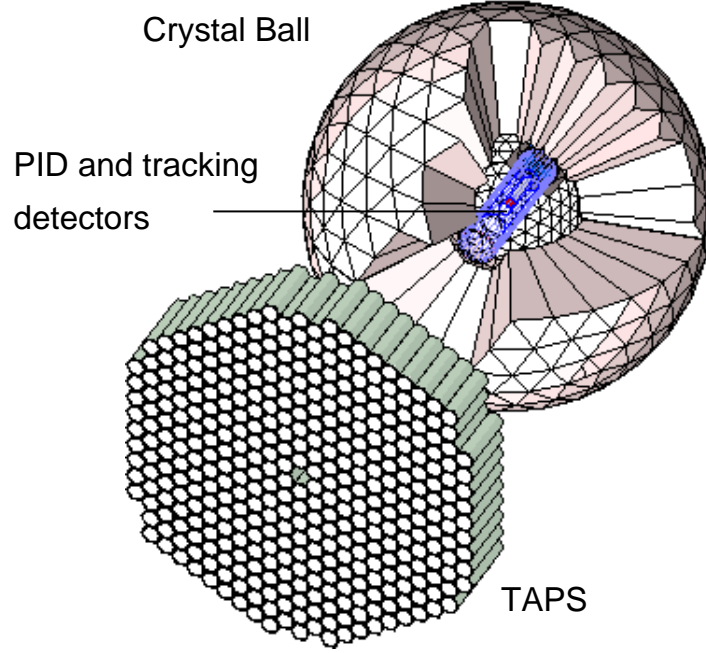


Figure 2: A cut-away view of the CB-TAPS detector system. The solid-angle coverage is approximately 96% of 4π .

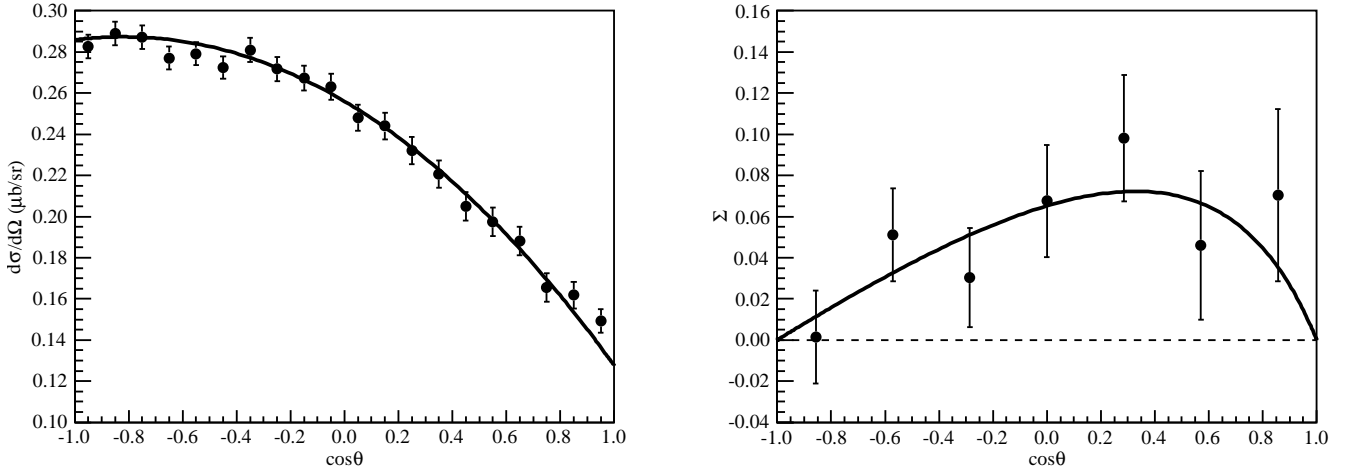


Figure 3: Preliminary CB-TAPS results for a photon energy of 163.9 MeV. Left Panel: Differential cross section versus $\cos\theta$. Right panel: Photon asymmetry versus $\cos\theta$. The errors are statistical and the lines are preliminary ChPT fits with s-, p-, and d-waves [13].

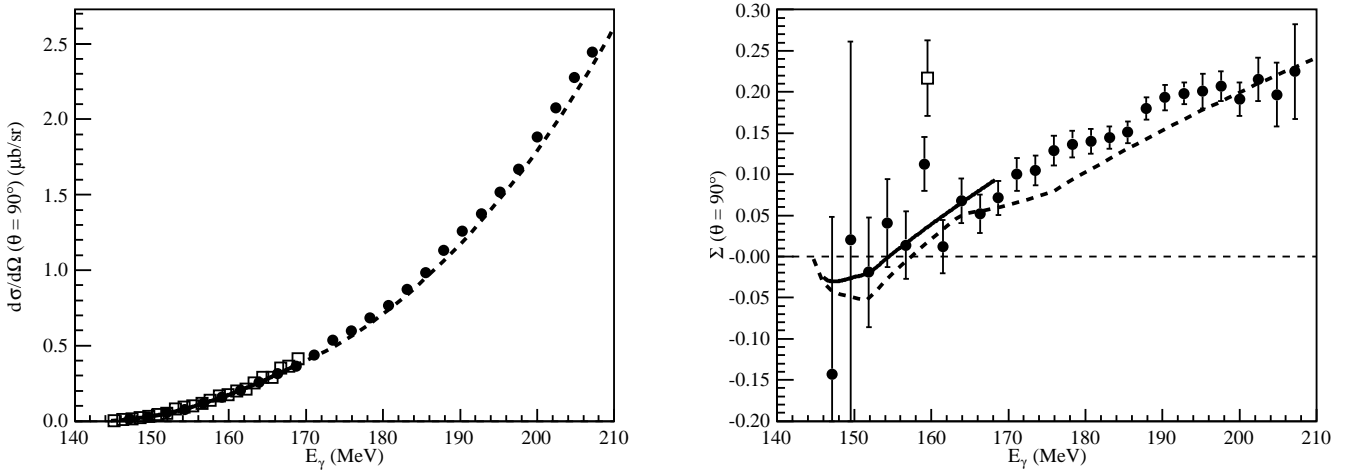


Figure 4: Preliminary CB-TAPS results (solid circles) of the differential cross section and photon asymmetry at pion CM angle of 90° as a function of incident photon energy compared to the older TAPS data [21] (open squares) as well as theory. The solid lines are preliminary ChPT fits to the new data [13] and the dashed lines are a dynamical model [27]. The ChPT fits have been done up to 165 MeV, but the issue of maximum energy of convergence will be explored. Errors are statistical only. Left Panel: Differential cross section. Right panel: Photon asymmetry.

the following way

$$\frac{d\sigma}{d\Omega}(\theta) = A_T + B_T \cos \theta + C_T \cos^2 \theta$$

where A_T , B_T , and C_T are the coefficients. The photon beam asymmetry is related to the transverse-transverse cross section

$$\frac{d\sigma_{TT}}{d\Omega}(\theta) = \sin^2 \theta (A_{TT} + B_{TT} \cos \theta + C_{TT} \cos^2 \theta)$$

through the polarized photon asymmetry Σ , where

$$\Sigma(\theta) = -\frac{d\sigma_{TT}}{d\Omega}(\theta) / \frac{d\sigma}{d\Omega}(\theta).$$

Here the effects of the d-waves will appear in all coefficients, but it is the B_{TT} coefficient where the effect is the most dramatic since it equals 0 if only s- and p-waves contribute. Our preliminary analysis indicates significant non-zero values which is the first direct experimental proof that the d-waves do contribute at low energies as predicted [13].

Analysis of the coefficients and multipoles is currently ongoing, and once finished will allow an accurate extraction of the s- and all three p-waves. More important, for the first time, the energy dependence of the p-waves will be obtained along with a definitive determination of d-wave contributions. The unitary cusp in the s-wave amplitude arising from charged pion re-scattering will also be examined, leading to the extraction of the cusp function for the real part of the electric dipole amplitude. These data provide the most stringent test to date of the predictions of Chiral Perturbation Theory and its energy region of convergence.

3 Target and Beam-Target Asymmetries

The development of a transverse polarized proton target (butanol frozen spin) has enabled us to access time reversal odd observables which are sensitive to the phases of the πN final states [17,

24, 25, 29]. We have performed precise measurements of the $\vec{\gamma}\vec{p} \rightarrow \pi^0 p, \pi^+ p$ reactions from threshold to the Δ resonance using circularly polarized photon beams and a transverse polarized target [30]. We have measured the polarized target asymmetry $\mathbf{T} = \mathbf{A}(\mathbf{y})$ [25, 26] for which the target polarization is perpendicular to the reaction plane. We also measured the double polarization observable $F = A(\gamma_c, x)$ (circularly polarized photons on a transverse polarized target) [25, 26] which is sensitive to the d-wave multipoles that have recently been shown to be important in the near threshold region [13]. Preliminary data from this experiment is shown in Figure 5 for a photon energy of 320 MeV. The first panel shows the missing mass plot which is useful to separate the π^0

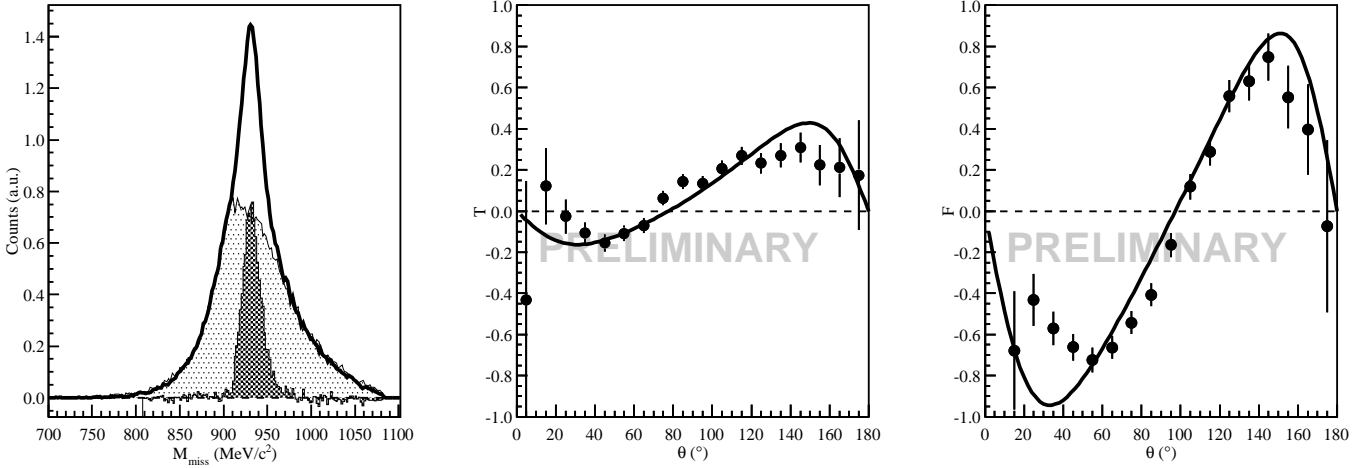


Figure 5: Preliminary results for a photon energy of 320 MeV. Left panel: Counts versus missing mass for the butanol target (unfilled histogram), carbon target (light grey histogram), and the difference due to the protons in the target (dark grey histogram). Centre panel: T asymmetry versus θ (the pion CM angle). Right panel: F asymmetry versus θ . The errors are statistical and the lines are predictions of the MAID model [31].

mesons produced from the protons from the other elements in the butanol target and in the target cell walls. We also have performed a background experiment in which a foamy carbon target with the same geometry as the butanol was measured. By subtracting the suitably normalized carbon target data from that of the butanol it can be seen that the proton target signal can be accurately extracted. Using this technique a preliminary analysis of part of the data are presented for the T and F asymmetries and compared to the predictions of the MAID model. Analysis of the data is currently under way.

The T asymmetry (time reversal odd) will measure the charge exchange scattering length $a_{cex}(\pi^+ n \rightarrow \pi^0 p)$ from the unitary cusp above the $\pi^+ n$ threshold [17, 25], which is a measure of the s-wave interaction between two unstable particles! We anticipate $\simeq 1\%$ statistical and $\leq 2\%$ systematic uncertainties, where the latter is dominated by the degree of target polarization. If isospin is conserved then $a_{cex}(\pi^+ n \rightarrow \pi^0 p) = a_{cex}(\pi^- p \rightarrow \pi^0 n)$. At the present time the right-hand side has been measured in pionic hydrogen with an error of $\simeq 1.5\%$ [32], and it is anticipated that future work will reduce the uncertainty. Any deviations from the isospin conserving limit will test isospin breaking due to the electromagnetic interaction and the strong interaction due to the mass difference of the up and down quarks predicted in ChPT [8]. Observation of T for the first time in the intermediate-energy region, combined with the other accurate data which we are obtaining, will provide us with information about the πN phase shifts for charge states ($\pi^0 p, \pi^+ n$) that are not accessible to conventional πN scattering experiments. This will enable us to test isospin con-

servation [24]. In addition these measurements will test detailed predictions of Chiral Perturbation Theory [28] and its energy region of convergence.

References

- [1] Y. Nambu, Phys. Rev. Lett. **4**, (1960) 380–382; Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122**, (1961) 345–358 and Phys. Rev. **124**, (1961) 246–254
- [2] See e.g. J. F. Donoghue, E. Golowich, and B. R. Holstein, *Dynamics of the Standard Model*, (Cambridge University Press, Cambridge, UK, 1994)
- [3] S. Weinberg, Phys. Rev. Lett. **17**, (1966) 616–621
- [4] V. Bernard and U.-G. Meißner, Ann. Rev. Nucl. Part. Sci. **57**, (2007) 33–60
- [5] V. Bernard, Prog. Part. Nucl. Phys. **60**, (2008) 82–160
- [6] A. M. Bernstein and S. Stave, Few Body Syst. **41**, (2007) 83–93
- [7] S. Weinberg, in *I. I. Rabi Festschrift*, (New York Academy of Sciences, N.Y., 1977) 185; A. M. Bernstein, in *Chiral Dynamics: Theory and Experiment*, A. M. Bernstein and B. Holstein editors (Springer-Verlag, 1995)
- [8] M. Hoferichter, B. Kubis, and U.-G. Meißner, Phys. Lett. B **678**, (2009) 65–71; Nucl. Phys. A **833**, (2010) 18–103
- [9] K. Nakamura et al., J. Phys. G **37**, (2010) 075021
- [10] H. Leutwyler, Phys. Lett. B **378**, (1996) 313–318
- [11] S. Weinberg, Physica A **96**, (1979) 327–340; J. Gasser and H. Leutwyler, Ann. Phys. **158**, (1984) 142–210; Nucl. Phys. B **250**, (1985) 465–516 and 517–538
- [12] For critical discussion of the meaning of low-energy theorems and a review of the literature see G. Ecker and U.-G. Meißner, Comm. Nucl. Part. Phys. **21** (1995) 347
- [13] C. Fernández Ramírez, A. M. Bernstein, and T. W. Donnelly, Phys. Lett. B **679**, (2009) 41–44. C. Fernández Ramírez, A. M. Bernstein, and T. W. Donnelly, Phys. Rev. C **80**, (2009) 065201 1–15
- [14] G. Colangelo et al., e-Print: arXiv:1011.4408 [hep-lat]
- [15] D. T. Madigozhin [NA48-2 Collaboration] AIP Conf. Proc. **1343**, (2011) 626–628
- [16] G. Colangelo, J. Gasser, A. Rusetsky, Eur. Phys. J. C **59** (2009) 777–793
- [17] A. M. Bernstein, Phys. Lett. B **442**, (1998) 20–27
- [18] A. M. Bernstein, in *Chiral Dynamics 2006: Proceedings of the 5th International Workshop on Chiral Dynamics, Theory and Experiment*, M. W. Ahmed, H. Gao, B. Holstein, and H. R. Weller editors, (World Scientific, NJ, USA, 2007) 3–16
- [19] R. Beck et al., Phys. Rev. Lett. **65**, (1990) 1841–1844
- [20] M. Fuchs et al., Phys. Lett. B **368**, (1996) 20–25
- [21] A. Schmidt et al., Phys. Rev. Lett. **87**, (2001) 232501 1–4
- [22] J. C. Bergstrom et al., Phys. Rev. C **53**, (1996) R1052–R1056; Phys. Rev. C **55**, (1997) 2016–2023
- [23] The πN data base can be found at the CNS Data Analysis Center. The lowest energy published πN scattering data at a kinetic energy of 20 MeV is H. Denz et al., Phys. Lett. B **633**, (2006) 209–213

- [24] A. M. Bernstein, πN Newsletter No. **11**, (1995), and article in preparation
- [25] A. M. Bernstein, M. W. Ahmed, S. Stave, Y. K. Wu, and H. Weller, Ann. Rev. Nucl. Part. Sci. **59**, (2009) 115–144
- [26] D. Drechsel and L. Tiator, J. Phys. G **18**, (1992) 449–497; A. S. Raskin and T. W. Donnelly, Ann. Phys. **191**, (1989) 78–142
- [27] S. S. Kamalov, S. N. Yang, D. Drechsel, and L. Tiator, Phys. Rev. Lett. **83**, (1999) 4494–4497; Phys. Rev. C **64**, (2001) 032201 1–5
- [28] V. Bernard, N. Kaiser, and U.-G. Meißner, Nucl. Phys. B **383**, (1992) 442; Int. J. Mod. Phys. E **4**, (1995) 193–344; Phys. Rev. Lett. **74**, (1995) 3752–3755; Eur. Phys. J. A **11**, (2001) 209–216
- [29] B. Ananthanarayan, Phys. Lett. B **634**, (2006) 391–398
- [30] M. Ostrick, D. Hornidge, W. Deconinck, and A. M. Bernstein, spokespersons, MAMI proposal A2-10/09, (2009)
- [31] D. Drechsel, O. Hanstein, S. S. Kamalov, and L. Tiator, Nucl. Phys. A **645**, (1999) 145–174; Eur. Phys. J. A **34**, (2007) 69–97
- [32] D. Gotta et al., AIP Conf. Proc. **1037**, (2008) 162–177